Indian J. Phys. **72B** (2), 125-136 (1998)

IJP B
— an international journal

An analysis of lightning channels, charge structure and associated atmospheric radio noise

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Received 26 November 1997, accepted 24 February 1998

Abstract Radar measurements and model studies are combined to investigate the physical structure of lightning in thunderclouds. Lightning echoes are treated as volume targets and comparisons with measurements show that the wavelength dependence is highly variable. Implications for charge rearrangement by thundercloud lightning are considered in the paper. Some data on the characteristics of atmospherics from lightning discharges have been estimated to examine their contribution to the intensity of noise in space. The results obtained from the analysis are critically discussed pointing out the observational difficulties in such measurements.

Keywords : Lightning, thundercloud, atmospherics

PACS Nos. 92.60. Pw, 92.60. Qx, 52.80. Mg

1. Introduction

Use of radar is undoubtedly an effective way for locating the lightning distribution in real time and to obtain its time structure. A number of observers have reported [1-4] radar echoes from lightning discharges. At the end of the discharge, recombination of the free charges occurs within a few milliseconds and an echo is no longer obtained. By using radar, it has become possible to study certain processes in lightning which cannot be achieved by other means. As the entire event from leader stroke to recombination takes place in a few tenths of a second, the direction of the stroke is difficult to predict. Most of the studies of lightning were seriously limited because of the shorter wavelengths radar (*S*-band) and linear polarization. In this paper, we report the detection of lightning, even in intense precipitation, using UHF-band radar at Millstone Hill (42.6°N, 288.5°E), in the town of Westford, about 40 miles north-west of the MIT Campus in Cambridge. The operating characteristics of these radars are presented in Table 1.

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Table 1. Radar characteristics.

Wavelength	11cm	68 cm
Antenna gain	41.3 dB	43.6 dB
Beam-width	1 4°	1.0°
Pulse length	1 sec	3 sec
Pulse repetition rate	721 Hz	500 Hz
Pulses per integration	128	Analog recording
Polarization	Linear (horiz.)	Circular

The most important parameter that is measured by using meteorological radar is the reflectivity of the scattering volume. From a knowledge of reflectivity, by using suitable empirical relations, one may deduce useful meteorological quantities like rainfall rate and liquid water content. Furthermore, severe storms can often be identified by their high reflectivities. In order to determine reflectivity, the quantity which is to be measured is the power received. From the average power received (P_r) and the radar equation, the volume reflectivity η can be calculated. If it is then normalized for wavelength, we get the reflectivity factor z_e. Some interesting radar observations of lightning are presented here and thereby a therorctical consideration is made.

It is now generally accepted that radar echoes are reflections from highly ionized air (plasma) created by the lightning discharge. The interpretation of these observations has been complicated both by the nature of the lightning plasma and by the geometry with which the plasma is distributed in space. This twofold complication is undoubtedly responsible for the great range of interpretations of the echo observations, which runs the gamut from a volume-filling under-dense plasma [5] to an assemblage of channels composed of under-dense plasma [6], to single channels composed of over-dense plasma [7, 8]. This study is also concerned with new observations and interpretations of radar lightning echoes which are intended to provide a clearer picture of lightning structure, as well as atmospheric radio noise originating in natural sources.

2. Reflectivities and range dependence of lightning echoes

Observations of the volume reflectivity of lightning versus radar range are shown in Figure 1 for several hundred echoes at S-band. Because of the absence of MIT observations at close

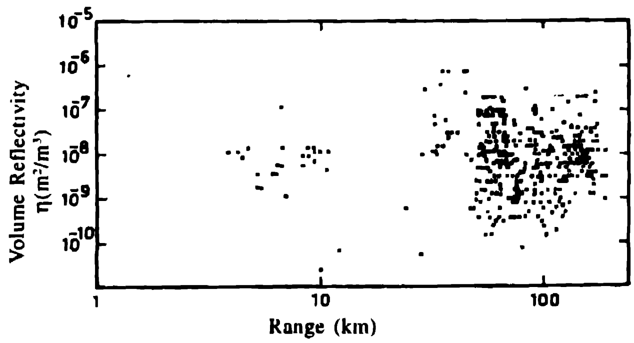


Figure 1. Summary of measurements of lightning volume reflectivity, η (m^2 m^{-3}) *vs* radar range at λ = 11 cm. Other S-band measurements reported by Holmes *et al.* [6] and Zrnic *et al.* [9], which are all in a range of 1–12 Km

range, we have included other S-band lightning observations [6, 9] in the 1–12 km range. Despite considerable scatter in the results at any given range, there is no evidence for a range dependence other than the $1/r^2$ dependence inherent with a volume target. Reflectivity measurements on more than 1000 lightning echoes have been obtained with the *S*-band radar. Measured η values range from 10^{-10} to 10^{-6} m^2m^{-3} corresponding to channel lengths per unit volume from 10^{-2} km km^{-3} to 10^2 km km^{-3}. Individual observations for a number of different thunder-storm days were organized in 2 km range intervals and arithmatically averaged to produce the plotted points (Figure 2). Lightning echoes exhibit considerable variability ; the standard deviation of these averages (20 to 150 values) is still a factor of 2-3 Superimposed on the log-log plot in Figure 2 are the straight line behaviours expected for point targets ($\eta \sim R^{-2}$), line targets ($\eta \sim R^{-1}$), and volume targets ($\eta \sim R^0$). The line of least squares fit through the averaged data points has a slope of – 0.06 and is therefore, most consistent with the volume target range dependence.

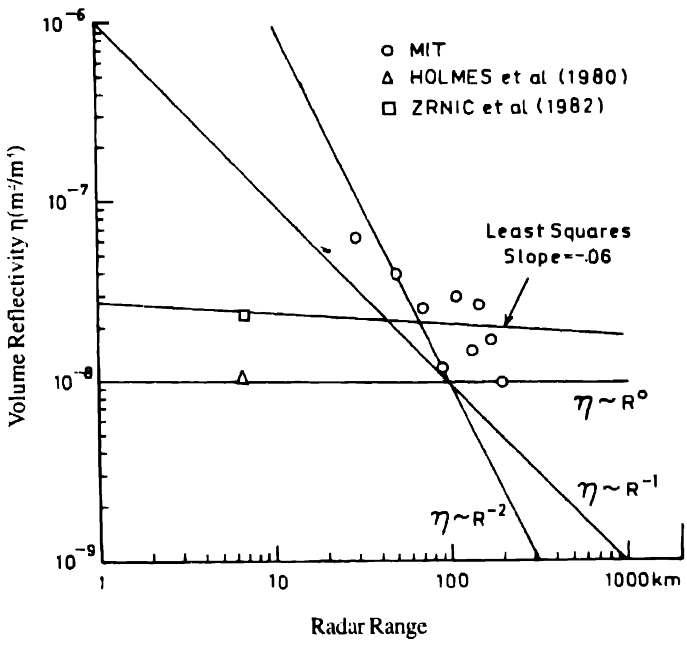


Figure 2. Volume reflectivity of lightning *vs* radar range at 11 cm

3. Comparison of theory with observations

A comparison is based on considerations of electrostatics and is illustrated in Figure 3. The charge redistributed by lightning is responsible for reducing the electric field within the cloud by a factor *f* which is 40-50% on the average and this factor has been taken as an estimate of the large scale neutralization of charge. In this model, a statistically homogeneous tree structure of positive polarity intrudes into a uniform background space charge ρ of negative polarity (Figure 3a). The tree is characterized by a channel length per unit volume L_v, and two scales associated with the channels making up the tree : the hot channel radius which is of the order of centimeters or less and the surrounding ion channel radius R, which is determined by the breakdown strength of air [10] and is of the order of 10 meters. In this model, the positive charge resides at the surface of the ion channels with surface charge density σ. Figure 3b shows a cross section through the idealized tree. The large scale neutralization condition becomes

$$L v \sigma \, 2\pi R = f \rho .$$

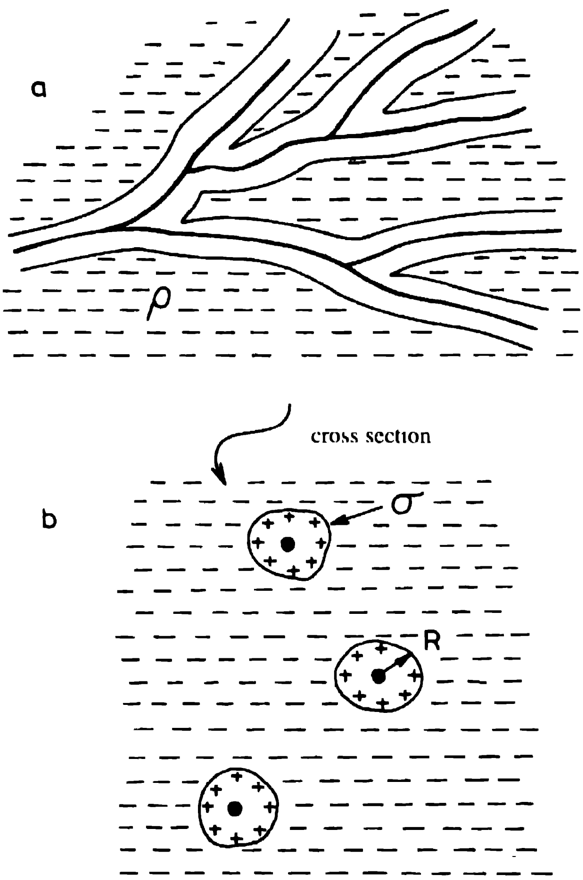


Figure 3. Constraints imposed by electrostatics on the channel length per unit volume associated with lightning

The electric field at the surface of the ion channel is assumed to be at the dielectric breakdown threshold

$$\sigma = \varepsilon_0 E_c .$$

Solving for L_v from

$$L_v = \frac{f\rho}{2\pi \varepsilon_0 R E_c} ,$$

and taking values $f = 0.4$, $\rho = 2 \times 10^{-9}\,\mathrm{C/m^3}$, $E_c = 10^6\,\mathrm{V/m}$, $R = 10\,\mathrm{m}$, $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F/m}$, we have $L_v = 4\,\mathrm{km/km^3}$ which is in good agreement with values inferred from the radar observations [9]. Note that in order to achieve this agreement, a channel size very different from the over-dense hot channel radius must be invoked.

The radar wavelength dependence of the lightning echoes is a valuable test for both plasma condition and geometry, and of several earlier measurement interpretations. Radar cross sections for large scale under-dense plasma blobs are expected to vary as λ^2 [11]. The cross sections of under-dense plasma channels (and assemblages of channels) depend exponentially on λ, $\sigma \sim \exp\left(\frac{-8\pi^2 a^2}{\lambda^2}\right)$ [12]. The returns from long thin over-dense plasma channels will vary approximately as $\lambda^{0.5}$ (13,14). For comparison with measurements, we have included these predictions with η values reported in the literature and the measurements of this study. Most previous investigators have reported lightning radar cross sections as σ in m^2, and these values were converted to volume reflectivity η by dividing σ by the appropriate pulse resolution volume. The mean η values are plotted as a function of radar wavelength in the log-log plot in Figure 4. For the very long wavelength radars, the lightning target may depart substantially from volume and lead to unrealistically small η values.

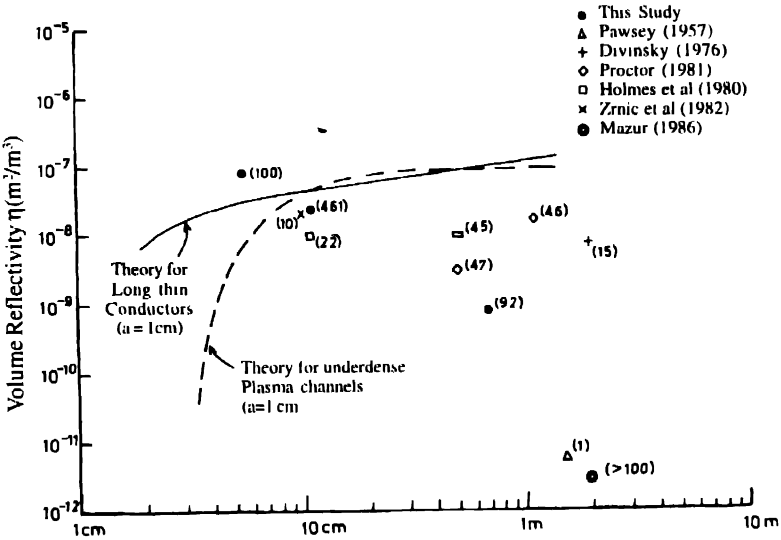


Figure 4. Mean volume reflectivity *vs* radar wavelength The figure includes values obtained by other measurements

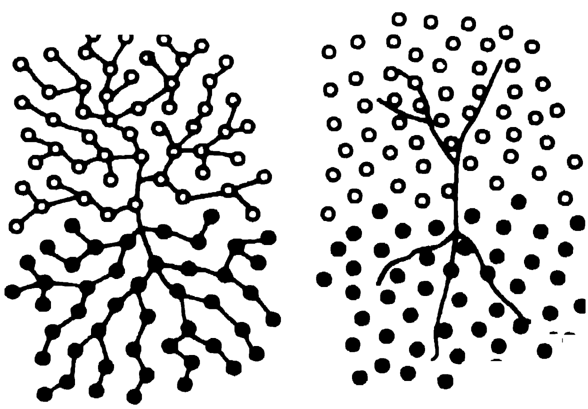
The general trends in the lightning echo wavelength dependence are clearly inconsistent with the predictions for both under-dense plasma blobs and under-dense plasma channels, both of which, have cross sections increasing with increasing wavelength. It is interesting to note that certain models for conductive surfaces with random topography exhibit a λ^{-2} wavelength dependence for backscatter (15). The incorporation of small scale tortuosity in the wire modelling moves the wavelength dependence in that direction (*i.e.* away from a power law exponent of 0.5), but we still cannot adequately explain the strong inverse wavelength dependence, which is mostly marked for the weaker echos. The wavelength dependence for conductive, randomly distributed short dipoles is (like precipitation particles) λ^{-4}, and we are tempted to argue that weak lightning targets are composed of disconnected over-dense channel segments, but then we cannot easily explain the persistent currents which are known to flow for tens of milliseconds over distances of kilometers (16).

Comparisons with the lightning echo distributions demonstrate that precipitation is a formidable noise factor for lightning observations at the shorter wavelengths. None of the echoes at $\lambda = 5$ cm would have been detected, had they originated in 55 dBZ precipitation cores ; half the echoes would have been masked by 30 dBZ precipitation. At $\lambda = 11$ cm, masking is not a significant problem in 30 dBZ regions, but again in maximum reflectivity regions only the very strongest lightning echoes will be detected.

Observations of lightning at X-band ($\lambda = 3.2$ cm) have been reported by Ligda [17], Browne [18] and Foster [19]. Browne's quantitative estimate is discussed by Dawson [12]. The calculated volume reflectivity ($\eta = 2 \times 10^{3}\,\mathrm{m}^2/\mathrm{m}^3$) follows the trend established at longer wavelengths, but is the largest value in Figure 4 by three orders of magnitude. We regard it suspiciously. In any case, the results of this study indicate that the rarity of radar lightning detection at 3.2 cm wavelength [6] and the marginality of detection at 5 cm (20) are a result of masking by the precipitation, and not the effect of an under-dense plasma channel. While arguments have been presented for an over-dense plasma being the dominant contributor to the radar target on the hundred millisecond time scales characteristic of lightning, it should be noted that wherever the plasma temperature drops significantly below about 4000°K (depending on radar wavelength), the plasma is expected to take on an under-dense behaviour.

4. Charge rearrangement in thundercloud discharge

The foregoing results concerning lightning geometry have important implications for questions which have arisen in recent years about the nature of the lightning discharge itself (21). Two distinct pictures of charge rearrangement in a thunder-cloud discharge are illustrated in Figure 5.



(a) (b)

Figure 5. Schematic illustration of (a) complete charge neutralization (b) coarse charge rearrangement due to intracloud lightning discharge

According to one view, the discharge establishes ionized conducting paths to every charged particle in the cloud, and thereby achieves a complete electrical neutralization of the system. According to the second view (22), discharge paths bring opposite charge amongst the charged particles of the cloud, thereby reducing the overall electric energy but failing to achieve microscopic neutralization. If there are N charged particles per unit volume in the cloud, we know from dimensional analysis that the average distance between particles will be $N^{-1/3}$, and that the total path length per unit volume for microscopic neutralization will be approximately $L_v = N^{-1/3} \cdot N = N^{2/3}$ (m/m^3). If the electric charge is carried by precipitation particles with $N = 10^3 \mathrm{m}^{-3}$, then $L_v = 10^2$ m/m^3 = 10^8 km/km^3. If the electric charge is carried by cloud particles with $N = 10^9 \mathrm{m}^{-3}$, then $L_v = 10^{12}$ km/km^3. These estimates are to be compared with the average over-dense channel length per unit volume $L_v = 4$ km/km^3, derived from the lightning echo results. While electric charge is undoubtedly transferred *via* underdense plasma channels (which are not strong contributors to the radar echoes), the 7-11 order of magnitude difference here is strong evidence against the neutralization picture for lightning discharges. This conclusion is independent of whether precipitation or cloud particles carry the bulk of the electric charge.

A second question raised by this study concerns the origin of the persistent quasi-steady current in lightning which is believed to be responsible for the persistence of radar echoes on hundred millisecond time scales (20). Independent observations (16) have shown that this total current is in the range of ten to several hundred amperes.

Again, two distinct hypotheses suggest themselves for the maintenance of this current. According to the first, the charged particles in the cloud continuously migrate towards the conductive dendrite and thereby guarantee continuous charge transfer. According to the second hypothesis, the dendrite is a highly dynamic one and continues to grow into new regions of space charge, thereby transferring electric charge and maintaining the current.

The topological similarity between lightning and river networks noted earlier, suggests the use of Horton's laws (23) to test the validity of these hypotheses.

The charge transfer process in the first hypothesis depends on the total surface area of the lightning dendrite. Given the branching ratio γ_b the length ratio γ_l the channel radius a the order of the network s, and the length l_s of the main channel (of order s), one can calculate the total surface area as

$$A = \frac{2\pi a\, l_s\, (r_b)^{s-1}}{r_l} \; \frac{\dfrac{(r_b)^{s-1}}{r_l}}{(r_l / r_b)^{-1}}.$$

For representative values $a = 10^{-2}$ m, $l_p = 5 \times 10^3$ m, $s = 5$, $r_b = 3$, $r_l = 2$, we have A = 4000 m^2. To maintain a steady current of 100 amperes would require an average current density of

$$J = \frac{100\mathrm{A}}{4000\mathrm{m}^2} = 2.5 \times 10^{-2}\ \mathrm{A/m}^2.$$

If the electric field at the channel surface is everywhere near dielectric breakdown ($E_c = 10^6$ V/m), the requisite effective conductivity associated with the migrating particles is

$$\sigma = \frac{J}{E} = \frac{2.5 \times 10^{-2}\ \mathrm{A/m}^2}{10^6\ \mathrm{V/m}} = 2.5 \times 10^{-8}\ \mathrm{mhos/m}.$$

This number is at least 5 orders of magnitude larger than the measured conductivity in thunderclouds (13). The mobilities of charged cloud particles and precipitation particles are too small to account for the observed currents in this hypothesis.

The second hypothesis relies on the integrating effect of a large number of branch tips advancing into the space charge regions within the cloud. The total number of tips of first (smallest) order is easily determined as

$$N = r_b^{s-1}.$$

Taking again $r_b = 3$ and $s = 5$, we have

$$N = 3^{5-1} = 81$$

To achieve a total current of 100 A would require individual branch tip currents of 100/81 = 1.2 A. This number is in good agreement with currents associated with leaders in 10 meter gaps (24). Such a current should maintain an over-dense plasma response to radar. This hypothesis affords the better explanation for the maintenance of the quasi-steady lightning current than the migration of charge particles in the cloud. This hypothesis is also consistent with radar observations in which we often observe propagation along the radar beam.

5. Lightning characteristics as derived from atmospherics

The problem of measuring atmospheric noise has been under study at the University of Kalyani (22°58'N, 88°28'E) for the last couple of years as a part of noise and wave propagation investigation with a view to searching for a measurable characteristic of noise that would serve as a reliable index of its interference effect. The term atmospheric noise is used broadly to define and interfering radio waves originated by electrical disturbances of the atmosphere. These disturbing electromagnetic waves originate mainly from lightning flashes and have energy components throughout the radio frequency spectrum. Considering the chance occurrence of lightning discharges in time and the variability of orientation, current waveform and conditions over the propagation path, the instantaneous noise voltage induced in a receiving antenna will not depend in any regular way on time as a variable.

Although many space activities involve the reception of radio signals in space vehicles, little consideration appears to have been given to the intensity of radio noise which would be expected from sources on the Earth. In fact, in the design of some space experiments, particularly those involving the study of the ionosphere itself, it is required to know what is the flux of noise energy from below. This is especially true at frequencies somewhat higher than the critical frequency and also at very low frequencies where some noise can be transmitted in the whistler mode. It would be definitely useful to use a satellite for plotting the locations of lightning discharges which would improve knowledge of the distribution of radio noise on the Earth. An assessment of atmospheric noise in space from terrestrial thunderstorms and the possibility of measurements are of great interest in recent years.

5.1 Methodology :

As the propagation modes of atmospheric noise are different from those involved in propagation to a satellite, the available data on the world-wide distribution of noise do not by themselves enable the noise in space to be estimated. Hence, the following procedure is applied to gather informations.

(i) Estimates are made of the occurrences of number of lightning discharges with an emphasis in the mere stormy parts of the world by different techniques.

(ii) Estimation of energy and other characteristics from observations on single atmospherics originated in near storms at different frequencies.

(iii) The results obtained by above two processes are combined to deduce the noise at satellite heights, considering where possible, the ionospheric effects.

As far as the present observational techniques are concerned, the following properties of individual atmospheric are of interest :

(i) the energy required to estimate the total power radiated from a thunderstorm area ;

(ii) the peak field strength to determine whether a single atmospheric is detectable above the background noise ;

(iii) the time integral of the field strength relevant to measure the average field strength of noise, using a receiver with a linear detector and

(iv) the duration to determine where atmospherics will be distinguishable as separate entities or will merge into more continuous noise.

5 2 Theoretical consideration :

(i) Statistical approach on measuring atmospheric noise

The random-like voltage envelope appearing at the detector output is the noise voltage, the measurement of which is considered here. As an irregular function of time or time series $v(t)$, it may be treated by statistical methods. The average and the mean-square values of a sample of noise of duration Δt are the first and second statistical moments of the time series for the period (25). The n-th moment is given by

$$M_n = \int^{\infty} y^n f(y)\, dy, \tag{1}$$

where M_n is the n-th order moment, y is the amplitude variable and $f(y)$ is the probability density function defining the probability of occurrence of various values of y. In eq. (1), the noise $y(t)$ is taken as a stationary time series during the period Δt, which makes $f(y)$ a one-dimension distribution function. The series is essentially stationary if the period of observation is of the order of one to ten minutes. To describe a stationary time series by the method of moments, it is required to specify not only the first and second moments but the higher order moments as well.

(ii) Calculation of power flux at VLF for vertical discharges :

The field strength due to a vertical discharge is assumed to vary as the sine of the zenith angle. The mean square field strength is given by (26)

$$E^2 = 3000\,\pi^2 J N \sin^4 \phi,\ (\text{v/m})^2. \tag{2}$$

while the equivalent power flux density is $25\,\pi J N \sin^4 \phi$, w\m^2.

For $\phi = 45^\circ$, the flux density $= 19.6 J N$ w/m^2.

In practice, flux densities may be significantly greater than this. This is because ground discharges have horizontal components even though their general orientation is vertical. Hence, they can radiate energy towards the zenith.

5.3 Typical lightning discharge and the associated atmospherics :

Studies of atmospherics from nearby storms during the three years (1994-96) provide some properties of the vertically polarised field near the ground at a distance of about 10 km as confirmed by Radar from a typical lightning discharge. Table 2 reveals some characteristics of atmospherics from a discharge at a frequency of 10 kHz in a bandwidth of 1 kHz.

Table 2. Characteristics of atmospherics from a typical lightning discharge at 10 kHz

Characteristics	Value
Peak amplitude	1600 mV/m
Amplitude integral (= $\int e\, dt$)	5600 (μ V/m) sec
Integral of the amplitude squared (= $\int e^2\, dt$)	2.5×10^9 (μ V/m)^2 sec
Energy flux (= J)	3.3×10^{-6} Joules/m^2
Duration	~ 500 m/sec

The amplitude data given in Table 2 refer to the electric field as measured in a short vertical rod aerial at ground level. At VLF band, it is assumed that the radiation is mainly from return strokes which are on the average vertical. Assuming the ground as a good conductor, the field strength of the radiation varies as the sine of the zenith angle, as measured at the source provided that the length of the discharge is short compared to wavelength.

In order to study atmospherics as a source of radio noise, we have considered the distribution of the amplitudes or energies separately considering the cloud discharges and around discharges. By a close scrutiny of our results, it is seen that at 10 kHz, the cloud discharges tend to give the smaller values while ground discharges exhibit larger values. Our observation was then extended to frequencies of 21 and 27 kHz. Interestingly, no great amplitude difference between atmospherics was noted at such times from the two type of discharges.

6. Discussion and conclusions

A large number of lightning echo observations and comparisons with a model have led to the following informations :

(1) The lightning plasma is generally over-dense at all meteorological radar wavelengths, and hence responds like a metallic conductor for times on the order of hundreds of milliseconds. The hot air plasma is collisional, with a collision frequency comparable to the plasma frequency, but the collisional aspect leads to only small departures from perfect conductor behaviour.

(2) The lightning echo behaves as a volume target to radar. This behaviour is attributed to a three dimensional dendritic structure composed of over-dense channel segments which are long and thin compared to a radar wavelength. The present observations, though sufficiently improved for lightning investigation, suffer from various difficulties.

(3) Noise radiated by lightning is highly transient. The path followed by subsequent strokes does not manifest itself in UHF noise records, if these strokes do not radiate noise. Even if the receiving system is supplemented by installing electric fieldchange meters, the occurrence of subsequent strokes cannot always be identified.

(4) The records of sferic noise become difficult to study sometimes, when different regions of the same discharge are simultaneously active. Pulse-to-pulse observations and digital data collection can provide additional information with considerably greater accuracy and resolution.

(5) In order to study the temporal variations of the lightning plasma with sufficient resolution, we believe it is essential to implement a digital 'first in, first out' recording scheme for specifically chosen lightning events. We need to record the digitized pulse-to-pulse bipolar coherent video (both channels) in buffer memory and when a switch is thrown (prompted by the observation of a lightning event), the contents of the buffer memory (a few seconds worth of data in a pre-selected set of range gates) are recorded on magnetic tape for subsequent analysis.

Future studies should include more reliable measurements at the very long wavelengths (*e.g. L*-band) where masking by precipitation is substantially reduced.

Acknowledgments

We are grateful to Prof. E. R. Williams of MIT, USA, for valuable suggestions, encouragement and helps and to Prof. A. K. Sen of Institute of Radio Physics and Electronics, Calcutta for critical discussion. We are also thankful to the Director of India Meteorology Department for supplying some relevant data.

References

[1] Hubert P LaRoche and A Eybert *J Geophys. Res* **89** 2511 (1984)

[2] E R Williams, S G Geotis and A B Bhattacharya *J. Atmos. Sci.* **46** 1173 (1989)

[3] R E Orville *J Geophys. Res.* **96** 17131 (1991)

[4] A B Bhattacharya, B K Datta and R Bhattacharya *Indian J Radio Sp Phys.* **23** 323 (1994)

[5] D Atlas *Recent Advances in Atomospheric Electricity* ed. L G Smith (New York Pergamon) (1958)

[6] C R Holmes, E W Szymanski, S J Szymanski and C B Moore *J. Geophys Res* **85** 7517 (1980)

[7] A B Bhattacharya *Indian J Radio Sp. Phys.* **21** 294 (1992)

[8] V Mazur, W D Rust and J C Gerlach *J Geophys. Res.* **91** 8690 (1986)

[9] D S Zrnic, W D Rust and W L Taylor *J. Geophys. Res.*, **87** 7179 (1982)

[10] S A Colgate and C Mckee *J. Geophys Res.*, **74** 5379 (1969)

[11] M A Heald and C B Wharton *Plasma Diagnostics with Microwaves* (New York : Krieger Publishing) 1978

[12] G A Dawson *J. Geophys. Res.*, **77** 4518 (1972)

[13] L I Divinsky *An Effective Radar Crosssection of a Lightning Channel (in Russian) Atmospheric Electricity,* (Leningrand) 177 (1976)

[14] R E Orville *J. Geophys. Res.*, **99** 10833 (1994)

[15] P Beckmann and A Spizzichino *The Scattering of Electromagnetic Waves by Rough Surfaces* (New York : Pergamon) 1963

[16] P R Krhehel, M Brook and R A McCrony *J Geophys. Res* **84** 2432 (1979)

[17] M G H Ligda *Bull. Am. Meteor. Soc.* **31** 279 (1950)

[18] J C Browne *Nature* **167** 438 (1951)

[19] H Foster *Air Weather Service Technical Report* **AWSTR 105-97** November 1952

[20] D E Proctor *J Geophys. Res* **86** 12109 (1981)

[21] B Vonnegut *J. Geophys. Res.* **88** 3911 (1983)

[22] B Vonnegut and C B Moore *A Possible Effect of Lightning Discharge on Precipitation* (Precipitation Physics AGU Monograph) vol 5, ed H Weickmann (1960)

[23] R E Horton *Geol Soc. Am.* **56** 275 (1945)

[24] I Gallimberti *J. Phys* **40** 7 (1979)

[25] H Cramer *Mathematical Methods of Statistics* (Princeton . Princeton Univ Press) p.176, 1947

[26] F Horner and P A Bradley *J. Atmos. Terr. Phys* **26** 1155 (1964)